UNITED STATES PATENT APPLICATION

For

OPTICAL FIBER CLADDING WITH LOW
POLARIZATION-DEPENDENT COUPLING

Inventors:

Wayne V. Sorin
Hyo-Sang Kim
Seok-Hyun Yun

Prepared by:

BLAKELY SOKOLOFF TAYLOR & ZAFMAN LLP
12400 Wilshire Boulevard
Los Angeles, CA 90025-1026
(408) 720-8300

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OPTICAL FIBER CLADDING WITH LOW POLARIZATION-DEPENDENT COUPLING

CROSS-REFERENCES TO RELATED CASES

[0001]   This application is a continuation-in-part of U.S. Patent Application Serial No. 09/944,283, filed on August 30, 2001, which is a continuation-in-part of U.S. Patent Application Serial No. 09/738,282, filed on December 14, 2000, which is a continuation of Serial No. 09/426,060, filed October 22, 1999, now U.S. Patent No. 6,266,462, which is a continuation-in-part of Serial No. 09/022,413, filed February 12, 1998, now U.S. Patent No. 6,021,237, which claims priority to Korean Application No. 97-24796, filed June 6, 1997.

BACKGROUND OF THE INVENTION

1). Field of the Invention

[0002]   This invention generally relates to a method of preparing optical fiber with low polarization dependence for use in acousto-optic applications, and, more particularly, to an acousto-optic filter employing such a fiber to reduce polarization-dependent loss (PDL) in the filter.

2). Discussion of Related Art

[0003]   As an optical signal traverses an optical network, the signal is subject to

losses and nonlinear effects that result in signal attenuation and distortion. Amplifiers, such as erbium-doped fiber amplifiers ("EDFA's"), are typically placed approximately every 80 kilometers along an optical fiber to boost signal strength. However, such amplifiers impose their own distortions on the signal power spectral distribution (as a function of wavelength). One of the major distortions is caused by the non-uniform gain profile (as a function of wavelength) of the amplifiers, which imposes a non-uniform spectral distribution on the amplified signals. It is especially important in wavelength division multiplexed ("WDM") networks to maintain a uniform spectral distribution across all channels.

[0004] Static filters are often used to attenuate the signal power as a function of wavelength to achieve a substantially uniform power distribution. Static filters, however, cannot adapt to dynamically changing conditions such as amplifier aging, temperature variations, channel add/drop, fiber loss and other changes in components along the transmission line. Moreover, the required filter shape is dependent upon system configuration, e.g., the spacing between amplifiers. Static filter characteristics cannot be modified to compensate for these changes without replacing the filter itself.

[0005] To overcome these problems, it is known in the art to employ dynamic wavelength tunable filters to flatten or equalize the signal spectrum, as well as to obtain any desired spectral shape. One such filter is an all-fiber acousto-optic tunable filter ("AOTF") described in United States Patent No. 6,233,379, entitled

"Acousto-optic filter," which is assigned to the assignee of the present invention and incorporated by reference herein. As described in the patent, the all-fiber AOTF is a multiple notch filter, with a transfer function characterized by notch depth and center frequency (or wavelength).

[0006]   One problem with the all-fiber AOTF is that the effect of the filter on light in the fiber is polarization-dependent. For example, although the filter may attempt to place a notch at one desired center frequency, the notch will effectively be placed at a different center frequency for each polarization – splitting one notch into two. The relative frequency shift between the polarization-dependent notches causes a difference between the transmissions of the different polarizations through the filter as a function of frequency, which results in a polarization-dependent loss in the filter. It is desired to reduce the polarization dependence of light in optical fiber, and to thereby reduce PDL in an all-fiber AOTF.

SUMMARY OF THE INVENTION

[0007] This invention relates to a method of making optical fiber having low polarization dependence and an acousto-optical filter, generally of the kind described in U.S. Patent No. 6,266,462, with low PDL. Light propagating through a cladding thereof has a mode group having a first eigenmode propagating at a first speed and a second eigenmode propagating at a second speed. Manufacture of the fiber is controlled so that a difference between the first and second speeds is small. A difference between the speeds divided by the first speed is preferably less than 5×10^{-7}.

[0008] The optical fiber may be used for constructing an acousto-optical filter. The filter includes a support, and first and second mounts at spaced locations on the support. The optical fiber has first and second mounted portions secured to the first and second mounts respectively. A signal generator is operable to generate a periodic signal. An electro-acoustic transducer has a terminal connected to the signal generator and an actuating portion, the electric signal causing vibration of the actuating portion, and the actuating portion being connected to the interaction length so that the vibration generates a transverse wave traveling along the interaction length. Such a filter has the ability to reduce an amplitude of one or more selected wavelengths of light as the light travels through the interaction length.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009]   The invention is further described by way of example with reference to

the accompanying drawings, wherein:

[0010]   Figure 1 is a side view illustrating manufacturing of optical fiber;

[0011]   Figure 2 is a side view illustrating severing of a length of optical fiber

manufactured according to the process shown in Figure 1;

[0012]   Figure 3 is a cross-sectional side view of an interaction length of the

severed length of the optical fiber of Figure 2;

[0013]   Figure 4 is a view similar to Figure 3 after a section of a jacket of the

optical fiber is stripped;

[0014]   Figure 5A is a cross-sectional end view on 5-5 in Figure 4 illustrating

stresses in a cladding layer of the interaction length;

[0015]   Figure 5B is a cross-sectional plan view through a section of the optical

fiber;

[0016]   Figure 6 is a side view illustrating an apparatus that is used to anneal

the cladding layer of the interaction length;

[0017]   Figure 7 is a cross-sectional side view of an acousto-optical tunable

filter according to an embodiment of the invention;

[0018]   Figure 8 is a side view illustrating functioning of the filter;

[0019]   Figure 9 is a view similar to Figure 7 illustrating coupling of x-polarized

light into the cladding layer;

[0020] Figure 10 is a view similar to Figure 9 illustrating coupling of y-polarized light into the cladding layer;

[0021] Figure 11 is a graph illustrating transmission of x-polarized light and y-polarized light through a core of the fiber, both before and after annealing;

[0022] Figure 12 is a graph illustrating PDL before and after annealing;

[0023] Figure 13 is a three-dimensional representation of an intensity profile in a core of a fiber according to another embodiment of the invention;

[0024] Figure 14 is a three-dimensional representation of a second-order mode of light in a cladding of the fiber of Figure 13;

[0025] Figure 15 illustrates the distribution of electric fields of four eigenmodes of the second-order mode group shown in Figure 14;

[0026] Figure 16 is a graph illustrating a refractive index profile through a cross-section of the fiber;

[0027] Figure 17 is a graph which illustrates the axial component of a stress profile through the fiber;

[0028] Figure 18 is a graph which illustrates the radial component of the stress profile through the fiber;

[0029] Figure 19 is a graph which illustrates the circumferential component of the stress profile through the fiber;

[0030] Figure 20 is a graph which illustrates a fractional speed difference between the eigenmodes of Figure 15 against notch wavelength;

[0031] Figure 21 is a graph which illustrates PDL of the fiber used in a filter

such as the filter of Figure 7 against notch wavelength;

[0032]   Figure 22 is a two-dimensional view illustrating intensity of a first-order mode of light propagating through the cladding;

[0033]   Figure 23 illustrates eigenmodes of the first-order mode group of Figure 22;

[0034]   Figure 24 is a three-dimensional view of a first-order mode group of light in a cladding of an elliptical fiber;

[0035]   Figure 25 illustrates electric-field components of four eigenmodes of the mode group shown in Figure 24;

[0036]   Figure 26 is a side view illustrating how polarization dependence can be changed by modifying birefringence utilizing an ultraviolet (UV) beam; and

[0037]   Figures 27(a) and 27(b) are graphs illustrating modification of propagation speeds of eigenmodes due to the UV beam.

DETAILED DESCRIPTION OF THE INVENTION

[0038]   Optical fiber fabrication typically consists of two major steps: preform fabrication and fiber drawing. There are a number of different methods for preform fabrication, such as modified chemical vapor deposition (MCVD), outside vapor deposition (OVD), and vapor-phase axial deposition (VAD). Figure 1 shows a preform 10 that is manufactured utilizing the MCVD technique. The process is initiated with a silica tube 12, which eventually forms an outer cladding layer of a fiber. An inner cladding material 14 is deposited on an inner surface of the silica tube 12, and eventually becomes an inner cladding layer of the fiber. A core material 16 is deposited on the inner cladding material 14.

[0039]   A heat source 18 is located near an end of the preform 10. The heat source 18 heats the end of the preform 10 to approximately 2000°C to melt it. Rollers 20 engage with material melted out of the end of the preform 10. The rollers 20 rotate, thereby drawing an optical fiber 24 out of the preform 10. As the fiber is drawn, a polymer jacket material (not shown) is coated on the fiber. The optical fiber 24 shown here is a single-mode fiber which is composed of the materials 12, 14, and 16, and is rolled into a roll 26.

[0040]   In Figure 2, a length 28 of the fiber 24 is paid out from the roll 26 and cut from the remainder of the fiber on the roll 26 for the purpose of constructing an optical filter according to the invention. Figure 3 illustrates in cross section a portion of the severed length 28. The optical fiber 24 includes a glass core 30

made of the core material 16, a cladding layer 32 surrounding the core 30, wherein the cladding layer itself may include an inner cladding layer 32A surrounding the glass core 30, and an outer cladding layer 32B surrounding the inner cladding layer 32A. A jacket 34 surrounds the cladding layer 32B.

[0041] As part of the process of constructing a filter according to the invention, a portion of the jacket 34 is removed to expose a section 36 of the fiber. A number of techniques may be employed to remove the jacket, including mechanical stripping and exposure to hot sulfuric acid, among others. Figure 4 illustrates the severed length 28 after a portion of the jacket is stripped from the section 36. First and second portions 38A and 38B of the jacket remain on the cladding layer 32. The portions 38A and 38B are located on opposing sides of the stripped section 36.

[0042] In order to achieve guiding characteristics, the core 30 is designed to have a higher refractive index than the cladding region by adding impurities such as GeO_2 and P_2O_5 to the SiO_2 basis of the core material 16. Such impurities in the core 30 not only create the required refractive index difference with respect to the cladding layers 32A and 32B, but also make the coefficient of the thermal expansion (CTE) and the melting temperature different from that of the cladding. Therefore, when the preform is fabricated at a high temperature of approximately 2000°C and cooled down to room temperature, a significant amount of stress is generated in the core 30 and the cladding layers 32A and 32B. This inherent stress is called "thermally-induced stress."

[0043]   Moreover, when the preform 10 is pulled to the optical fiber 28 at the drawing tower, the optical fiber is exposed to a drawing tension of typically 100 - 1,000 N, and this stress becomes frozen in the optical fiber 24 while the optical fiber 24 is cooled down to room temperature. Therefore, an additional stress field is created in the optical fiber, which is called "mechanically-induced stress."

[0044]   Figures 5A and 5B show the combined stress profile. The core is under axial, radial, and tangential tensile stress. The cladding 32A and 32B is under radial tensile stress and under axial and tangential compressive stress. There is thus a discontinuity of the stress field in the core-cladding interface.

[0045]   According to the invention, the cladding layer 32 of the stripped section 36 is then annealed utilizing an apparatus 50, as shown in Figure 6. The apparatus 50 may employ, for example, a modified CW-200 Fused Coupler/WDM workstation sold by Lightel Technologies, Inc. of Kent, Washington. The apparatus 50 includes a support structure 52, first and second attachment formations 54 and 56 respectively, a flame nozzle 58, and a hydrogen source 60.

[0046]   The attachment formation 54 is rigidly secured to the support structure 52. The attachment formation 56 is movably secured to the support structure 52. The hydrogen source 60 is connected to the flame nozzle 58. The flame nozzle 58 is secured to the support structure 52 for movement between the attachment formations 54 and 56.

[0047]   In use, the portions 38A and 38B of the jacket 34 are attached to the first

and second attachment formations 54 and 56, respectively. A force F is applied, which tends to move the attachment formation 56 away from the attachment formation 54, thereby creating a tension in the stripped section 36.

[0048]   Hydrogen from the hydrogen source 60 flows to the flame nozzle 58 and is lit at an exit from the nozzle 58 to create a flame 64. The nozzle 58 and the flame 64 are located above the stripped section 36 so as to heat the stripped section 36 from above. Hydrogen may be preferred to any other source of fuel because hydrogen combustion does not produce carbon or hydrocarbon byproducts that may deposit on the cladding layer 32. Those skilled in the art will recognize that electro-resistive and other heating sources may be employed in the present invention instead of the hydrogen flame described in this example.

[0049]   The nozzle 58 moves in a direction 66 parallel to the longitudinal axis of the stripped section 36. The advancing flame 64 heats areas of the stripped section 36 as those areas are exposed to the flame 64. Heating of the stripped section 36 is primarily due to radiation from the flame 64. Regions of the stripped section 36 trailing the flame 64 are allowed to cool. Cooling of the stripped section 36 is primarily due to convection of the heat to ambient air. The force F compensates for heat-induced elongation of the stripped section 36 by moving opposing ends of the stripped section 36 apart. The fiber is heated and cooled without the core 30 expanding by more than 20%.

[0050]   The effect of heating and cooling the stripped section 36 is that the cladding layers 32A and 32B are annealed. Fiber formed by modified chemical

vapor deposition has stress characteristics that are particularly conducive to the beneficial effects of this process.

[0051]   The flame 64 may be in the range 1-20 mm wide as measured along the stripped section 36. The flame 64 may be held at a distance of 0.1-5 mm, or more particularly, 0.5- 5mm from the stripped section 36. Movement of the flame in the direction 66 may be at a speed of 1-50 mm per second, or, more particularly, 1-10 mm/s. The stripped section 36 may be heated to a temperature between 500-1300°C, and, more particularly, to between 800-1000° C. The force F may be in the range 0.05-0.5 N, or, more particularly, 0.05-0.15 N, maintained substantially constant.

[0052]   Figure 7 of the accompanying drawings illustrates an acousto-optic filter 120 constructed according to an embodiment of the invention. The filter 120 is of the kind described in U.S. Patent No. 6,266,462, issued July 24, 2001, which is incorporated herein by reference. The filter 120 includes a mounting construction 122, the severed length 28 of the optical fiber, and an electrical signal generator 130.

[0053]   The mounting construction 122 includes a heat sink 132, an acoustic wave generator, such as a piezo-electric transducer 134, an acoustic wave propagation member 136, such as an aluminum horn, an outer tube arrangement 138, and an end plug 140.

[0054]   Gold terminals are sputtered on opposing surfaces of the piezo-electric transducer 134. One terminal is located against the heat sink 132 and attached to

the heat sink 132. The base of the acoustic wave propagation member 136 is then attached to an opposing terminal of the piezo-electric transducer 134.

[0055]   Openings are made in the heat sink 132, piezo-electric transducer 134, and acoustic wave propagation member 136 to form a continuous passage. The end of the severed length 28 having the first portion 38A of the jacket is inserted through the opening of the acoustic wave propagation member 136, whereafter it is inserted through the openings in the piezo-electric transducer 134 and the heat sink 132.

[0056]   The second portion 38B of the jacket is then located in a groove in the end plug 140. A resin is then placed in the groove and allowed to cure, thereby securing the second portion 38B of the jacket to the end plug 140.

[0057]   Resin is also applied to the fiber 24 where it protrudes from a tip 150 of the acoustic wave propagation member 136, and flows into the tip 150 of the acoustic wave propagation member 136. The resin then cures and secures the fiber 24 to the tip 150 of the acoustic wave propagation member 136.

[0058]   A damper 152 is located on the optical fiber 142. The damper 152 is coaxially disposed on the stripped section 36 adjacent to the second portion 38B of the jacket. The length of exposed fiber from the tip 150 to the end of the damper 152 nearest the tip 150 is the "interaction length 37" of the filter. Generally, the interaction length or "interaction region" is the length of fiber in which light is coupled from one mode to another, and, more particularly in this case, the portion of the exposed section 36 not covered by the damper 152.

[0059]   An end 154 of the outer tube arrangement 138 is then located over the second portion 38B of the jacket and moved over the end plug 140 until it contacts a surface of the heat sink 132. A second, opposing end 156 of the outer tube arrangement 138 is located over the end plug 140. The positioning of the end plug 140 is then adjusted within the end 156. By adjusting the positioning of the end plug 140, the interaction length 37 of the optical fiber 142 is tensioned by about 0.2 N to eliminate slack. When a predetermined tension in the interaction length 37 is reached, a resin is applied to an interface between the end plug 140 and the end 156. The resin is allowed to cure, thereby securing the end plug 140 stationarily within the end 156. The tension of the interaction length 37 is thereby set.

[0060]   The signal generator is connected to the transducer 134 through leads 160 and 162. The lead 160 couples to the heat sink 132, which is itself electrically coupled to a terminal on one face of the transducer 134. The lead 162 is electrically connected to the opposing face of the transducer 134, either directly to the terminal on the opposing face, or indirectly through the acoustic wave propagation member 136. The heat sink 132 and the acoustic wave propagation member 136 can be made of conductive aluminum so that the terminals on the opposing sides of the piezo-electric transducer 134 are at the voltages of the leads 160 and 162, respectively. A voltage potential is thereby created across the piezo-electric transducer 134.

[0061]   The signal generator 130 applies across the piezo-electric transducer 134

a voltage at one or more frequencies in the range of 0-20 MHz, or more particularly, 0-3 MHz. The voltage signal applied across the piezo-electric transducer 134 causes opposing surfaces of the piezo-electric transducer 134 to vibrate relative to one another in a direction transverse to a longitudinal axis of the interaction length 37. Adjusting the frequency and amplitude of the electrical signal applied to the transducer results in a corresponding change in the frequency and amplitude, respectively, of the mechanical vibration of the transducer. Those skilled in the art will recognize that the invention may employ acoustic wave exciters other than the acoustic wave exciter formed from the combination of the signal generator 130, transducer 134, and acoustic wave propagation member 136 described herein.

[0062]   Vibrations of opposing surfaces of the piezo-electric transducer 134 are transferred through the acoustic wave propagation member 136 to the tip 150 thereof. The tip 150 vibrates periodically in response to the change in the voltage. Movement of the tip 150 is transferred to the end of the interaction length 37 closest to the tip 150.

[0063]   Figure 8 illustrates how vibration of the tip 150 imposes acoustic waves in the interaction length 37. In the present example, the waves are y-direction transverse flexural waves that travel along the interaction length 37 from the tip 150 to the damper 152. The damper 152 is designed to absorb the waves or otherwise minimize reflection of the waves back to the tip 150. The creation of a standing wave is thereby prevented.

[0064]   In use, the filter 120 is inserted into a fiber optic transmission line. A

light signal is transmitted through the core 30. The light signal may be

modulated as a WDM signal having many channels, each at a different

wavelength. For various reasons, including the non-uniform gain profiles of

amplifiers along the fiber optic transmission line, the intensity of light may differ

from channel to channel at the point where the light enters the optical fiber 142 of

the filter 120.

[0065]   The effect of the acoustic waves in the interaction length 37 is that the

intensity of selected wavelengths of light traveling through the interaction length

37 is attenuated by coupling these wavelengths from a mode in the core into one

or more modes in the cladding layer 32 of the interaction length 37. This

coupling creates a notch in the transmission spectrum centered at each selected

wavelength. By changing the frequency of the applied electrical signal, and thus

the frequency of the acoustic waves in the interaction length 37, the center

wavelength of the notch can be altered. Furthermore, by changing the

magnitude of the applied voltage (and thereby the magnitude of the acoustic

wave), the depth of the notch (representing the amount of light coupled to the

other mode) can be changed. By cascading multiple acoustic exciter/interaction

length combinations and/or applying multiple acoustic frequencies with each

exciter, a combination of notches of different optical center frequencies and

depths may be achieved, thereby allowing creation of a desired filter transfer-

function as described in Serial No. 09/738,282. Such a filter may be employed

for gain equalization purposes. Those skilled in the art will recognize that, as an alternative to coupling light between core and cladding modes, an AOTF may also couple light between different core modes. Further details of the functioning of the filter 120 are described in U.S. Patent No. 6,266,462 referenced above.

[0066]   Figures 9 and 10 illustrate how light is coupled into the cladding layer 32 after application of an acoustic wave. These figures are for conceptual purposes only, and do not necessarily reflect the actual intensity distribution in the fiber. Light traveling in the core mode in the core 30 couples into both an x-polarized cladding mode including regions 70 and 72 in the cladding 32 (as shown in Figure 9), and into a y-polarized cladding mode including regions 80 and 82 (as shown in Figure 10). X-polarized and y-polarized components of light traveling in the core couple preferentially into corresponding x-polarized and y-polarized cladding modes, as shown in Figures 9 and 10, respectively. The arrows in Figures 9 and 10 indicate the direction and phase differences of the polarization of the light in each mode.

[0067]   The center wavelength λ_0 of light coupling into the cladding layer 32 is a function of the index of refraction β of the material of the cladding layer 32. At different points in the fiber, stress in the cladding layer changes the index of refraction β to an effective index of refraction β_{eff} which is different from the index of refraction β without any stress in the cladding layer 32. As a result of this stress-induced change in refractive index, the center wavelength λ_0 shifts,

and is thus also recognized as a function of stress in the cladding layer 32.

[0068]   Referring to Figures 5A and 5B, there is a larger tensile stress in the x-direction than in the y-direction. The larger tensile stress in the x-direction results in an effective index of refraction in the x-direction β_{eff-x} which differs from the index of refraction β of the cladding layer 32 with no stress therein. The effective index of refraction in the y-direction β_{eff-y} is, however, substantially equal to the index of refraction β of the cladding layer 32 without stresses in the cladding layer 32. The effective index of refraction in the x-direction β_{eff-x} is thus different from the effective index of refraction in the y-direction β_{eff-y} due to the tangential stresses 40. Light coupling from the core 30 to x and y polarized modes, as shown in Figures 9 and 10, will thus be coupled at different center wavelengths, λ_{0-x} and λ_{0-y}.

[0069]   Figure 11 illustrates how the filter of Figure 7 filters light when the stresses are not reduced as in Figure 5. Wavelengths λ are shown on the abscissa and transmission T through the core 30 is shown on the ordinate. It can be seen that there is a relatively large difference between the center notch wavelength of x-polarized light λ_{0-x} and the center notch wavelength of y-polarized light λ_{0-y}.

[0070]   Annealing the cladding layer 32, as discussed with reference to Figures 5A and 5B, causes a reduction in tensile stress in the x-direction. A reduction in tensile stress in the x-direction causes a reduction in the stress difference between

the x- and y-directions and a corresponding reduction in the difference between the effective index of refraction in the x-direction β_{eff-x} and the effective index of refraction in the y-direction β_{eff-y}. There is also a corresponding reduction in the difference between the center wavelengths of x-polarized light λ_{0-x} and y-polarized light λ_{0-y}, respectively. Referring again to Figure 11, annealing causes the center notch wavelength of the x-polarized light λ_{0-x} to move towards the center notch wavelength of y-polarized light λ_{0-y} as indicated by the arrow. This reduction in the difference between the center notch wavelengths indicates a reduction in the polarization dependence of light coupling into the cladding layer, along with a corresponding reduction in the PDL of the filter.

[0071] Figure 12 illustrates the extent to which PDL is reduced. The PDL of the filter is defined by the following formula:

$$PDL = |T_x - T_y|, \tag{1}$$

where T_x is transmission in decibels (dB) of x-polarized light and T_y is transmission in dB of y-polarized light through the core 30. The PDL before annealing is represented by line 74 and the PDL after annealing is represented by line 76. The PDL before annealing is as much as 4 dB before annealing, and less than 1.0 dB, or, more particularly, less than 0.5 dB, after annealing. PDL is proportional to the slope of the notch profile at a constant difference of $| \lambda_{0-y} - \lambda_{0-y} |$. Therefore, PDL is inversely proportional to the notch width. The notch width is inversely proportional to the length of the optical fiber 142.

[0072]   Thermal annealing is not the only manner in which polarization dependence and PDL can be reduced. An example will now be described wherein polarization dependence and PDL can be reduced by fine-tuning dopant concentrations so as to obtain predetermined profiles of stress and refractive index.

[0073]   Figure 13 illustrates an intensity profile of light in a core of an optical fiber having a single-mode core. The intensity profile in the core is substantially Gaussian. Figure 14 illustrates an intensity profile of a second-order mode of light through a cladding of the fiber. The intensity has a first circular peak of 110 near the core, and a second circular peak 112 further away from the core. The second-order mode of light in the cladding as illustrated in Figure 14 includes four eigenmodes of electric fields. The eigenmodes are illustrated in Figure 15, and include TM_{02}, TE_{02}, HE^{o}_{21}, and HE^{e}_{21}. The eigenmode TM_{02}, for example, has an electric field which is radially outward from the core at the inner peak 110 and radially inward toward the core at the outer peak 112.

[0074]   The eigenmodes do not necessarily propagate at the same speed through the cladding. Polarization dependence can be reduced by reducing the differences in speeds between the eigenmodes. In the case where a y-directional flexural wave is created, it is required to reduce the difference in speed between the TM_{02} and TE_{02} eigenmodes in order to reduce PDL. The description that follows primarily focuses on reducing speed differences between the TM_{02} and TE_{02} eigenmodes. It should, however, be understood that acoustic waves other

than y-directional flexural waves may require speed matching of two or more of the other eigenmodes.

[0075] Figure 16 illustrates a refractive index profile through a cross-section of the fiber. The core of the fiber has a radius of approximately 4.15 microns, the inner cladding has a radius of approximately 8.3 µm, and the outer cladding has a radius of approximately 62 microns. The core has a refractive index of approximately 1.449. Both the inner and outer cladding layers have a refractive index of approximately 1.4448 (a refractive index of 1.000 indicates air).

[0076] The refractive index and stress profiles can be created by modifying dopant concentrations in the core and the cladding. In order to have the wave-guide characteristic, the core has the higher refractive index than the cladding by doping materials such as germanium. There are many doping materials known to us, which can either increase or decrease the refractive index in proportion to the concentration. The doping materials can affect the glass melting temperature as well as the coefficient of thermal expansion and thereby determine the residual stress profile of the fiber after the drawing process. In many cases, more than one doping material is deposited in the core and the inner cladding to achieve a desired refractive index profile and a desired stress profile. For example, fluorine is often used together with germanium to counteract the index increase by germanium in the inner cladding layer. Phosphorous is another material often used in the cladding layer to make the drawing process easy. Because of its low melting point, phosphorous is often used to create high

residual stress in the fiber. In general, the core and the cladding can consist of multiple dopant layers with different doping materials and concentrations, in order to have a desired index profile as well as a desired stress profile.

[0077] Figure 17 illustrates an axial component of stresses in the fiber. Stresses are induced due to differences in thermal expansion of the core, inner cladding, and outer cladding. In another embodiment, it may be possible to affect propagation speeds of eigenmodes by mechanically inducing stresses such as inducing a drawing tension. A positive value indicates tensile stress, and a negative value indicates compressive stress. The core is under a tensile stress of approximately 15 MPa. The inner cladding, having a radius of approximately 8.3 microns, is under a compressive stress of approximately 6 MPa. The outer cladding has substantially no stress in an axial direction. Radial and circumferential stresses are related to the axial stress in the fiber, and are indicated in Figures 18 and 19, respectively.

[0078] By fine-tuning the refractive index and axial stress profiles, fractional speed differences can be obtained as illustrated in Figure 20, which illustrates a fractional speed difference between eigenmodes against the wavelength of the notch. The line 118 indicates the difference in speed between TM_{02} and TE_{02}, divided by the speed of TM_{02}. The line 120 indicates the difference in speed between HE^{o}_{21} and TE_{02}, divided by the speed of HE^{o}_{21}. It can be seen that the absolute value of this fractional speed difference between TM_{02} and TE_{02} is less than 5×10^{-7} for all notch wavelengths between 1450 and 1750 nm. The fractional

speed difference, B, between TM_{02} and TE_{02} modes can be expressed by the following equation:

$$|B| = |(\text{speed of } TM_{02} - \text{speed of } TE_{02}) / \text{speed of } TM_{02}| < 5 \times 10^{-7} \qquad (2)$$

[0079] It may occur that a fiber having refractive index and axial stress profiles somewhat resembling the profiles shown in Figures 16 and 17 may not be fine-tuned to obtain fractional speed differences as illustrated in Figure 20 to reduce polarization dependence according to the invention. Stress and refractive index profiles are optimized so that the result side of the following equation is as small as possible, preferably below 5×10^{-7}:

$$\left| \int_0^{2\pi} \int_0^R \left(|E_{TM_{02}}|^2 n_{r\,stress} - |E_{TE_{02}}|^2 n_{\theta\,stress} \right) r\,dr\,d\theta - \left(n^{eff}_{TM_{02}\,no\,stress} - n^{eff}_{TE_{02}\,no\,stress} \right) \right| = result \qquad (3)$$

where:

R   is an outer radius of the cladding;

$E_{TM_{02}}$ is an electric field of an second-order of a transverse-magnetic mode, designated the TM_{02} mode;

$E_{TE_{02}}$ is an electric field of an second-order of a transverse-electric mode, designated the TE_{02} mode;

r is a radius of a location from a center point of the core;

θ is an angle between a reference line from the center point and a line from the center point to the location;

$n^{eff}_{TM_{02}\,no\,stress}$ is an effective refractive index of the TM_{02} mode, calculated by an optical waveguide theory when the fiber is under no residual stress, based on Maxwell equations;

$n^{eff}_{TE_{02}\,no\,stress}$ is an effective refractive index of the TE_{02} mode, calculated by an

optical waveguide theory when the fiber is under no residual

stress, based on Maxwell equations;

$n_{r\,stress}(r,\theta)$ is a refractive index as perceived by an electric field polarized in a

radial direction at a location (r,θ) when the location is under a

residual stress;

$n_{\theta\,stress}(r,\theta)$ is a refractive index as perceived by an electric field polarized in a

circumferential direction at a location (r,θ) when the location is

under a residual stress.

[0080]   Figure 21 illustrates PDL of the fiber when used in a filter such as in

Figure 7. The fiber is optimized so that PDL is zero at a notch wavelength of

approximately 1540 nm. In another embodiment, the fiber may be optimized so

that PDL is a minimum at other wavelengths, in particular between 1250 nm and

1650 nm. An increase of the notch wavelength above 1540 nm increases PDL,

and a decrease in the notch wavelength below 1540 nm also increases PDL. PDL

is below 0.5 dB at all notch wavelengths between 1450 nm and 1650 nm. The

PDL of Figure 21 was obtained under the following conditions:

[0081]   Interaction length: 10 cm;

[0082]   Acoustic wave: flexural wave with a linear vibration direction;

[0083]   Notch depth: 10 dB; and

[0084]   3 dB notch width: 4.5 nm.

[0085]   It may also be possible to match speeds of eigenmodes of other orders

of light propagating through the cladding. Figure 22 illustrates an intensity

profile of a first-order mode of light propagating in the cladding. The first-order mode has an intensity profile having a single circular peak 130. Figure 23 illustrates the eigenmodes in the first-order mode group illustrated in Figure 22. The eigenmodes include TE_{01}, TM_{01}, HE^{o}_{21}, and HE^{e}_{21}. The fractional speed difference between TE_{01} and TM_{01} may be reduced in order to reduce PDL in a filter with linear vibration of the fiber.

[0086]   Desired performance may also be obtained with fibers other than circular fibers. Figure 24 illustrates an intensity profile of a first-order mode of light in a cladding of an elliptical fiber. Figure 25 illustrates the electrical-field components of four eigenmodes of the first-order mode group of Figure 24. Polarization dependence and PDL may be reduced by minimizing fractional speed differences between two of the eigenmodes illustrated in Figure 25.

[0087]   Low polarization-dependent fiber may also be achieved without matching speeds of eigenmodes in a mode group. Low polarization dependence can, for example, be achieved by making speed differences between eigenmodes the same in two mode groups. For example, the speed difference between LP01x and LP01y can be made to be the same as that between the LP11x even and LP11y even. This can be achieved by optimizing the index and stress profiles of a fiber and the ellipticity of the core or cladding.

[0088]   One can also do post-trimming on a fiber to match the speed difference by using the birefringence creation and/or symmetric stress change by UV light, as will now be illustrated.

[0089]   In Figure 26, a photosensitive single-mode optical fiber 200 is exposed to a focused UV light 202 which travels along the axis of the fiber 200 over a predetermined length at a controlled speed. The photosensitive fiber is made by creating an oxygen-deficient bonding either through Ge, Sn, or B doping in the core or a hydrogen loading of a standard single-mode fiber. Preferably, the wavelength of UV light is 242-266 nm by using an Excimer laser or a frequency-doubled Ar+ laser. The energy of UV light is between 0.1-1J/cm^2. The polarization of the UV light is s-pol, aligned orthogonal to the axial axis of the fiber in order to enhance the index anisotropy for a given UV exposure. An index anisotropy as large as $\Delta n > 1 \times 10^{-5}$ is possible in the core, which is 0.1 ~ 10% of the change of the average refractive index. Since the index anisotropy is localized in the core, the cladding mode experiences much less birefringence than the core mode.

[0090]   Figure 27 illustrates this technique. Suppose the original fiber has nominally zero birefringence in the core mode and non-zero birefringence in the cladding mode, as shown in Figure 27. This causes polarization dependence in coupling between the two modes. The UV exposure creates birefringence in the core just enough to make the splitting in the core mode to be equal to that in the cladding mode. Therefore, the polarization dependence in mode coupling between the core and cladding modes becomes reduced. This is illustrated in Figure 27. By this means, the polarization-dependent loss (PDL) of an acousto-optic filter can be reduced to less than 0.5 dB at 4 nm width and 10 dB depth

notch.

[0091]   Ideally, traveling speeds satisfy the following equation:

$$|A - B| < 5 \times 10^{-7} \qquad (4)$$

where A is the fractional speed difference between LP01x and LP01y (i.e., A = (speed of LP01x − speed of LP01y)/speed of LP01x) in the core and B is the fractional speed difference between LP11x and LP11y (i.e., B = (speed of LP11x − speed of LP11y)/speed of LP11x) in the cladding. In the case of a fiber having a circular core, such as in Figure 16, A is approximately zero, so that the result of the equation $|A - B|$ is the same as $|B|$. According to eq(2), $|B| < 5 \times 10^{-7}$, so that $|A - B|$ is also smaller than 5×10^{-7}.

[0092]   It is also known that UV exposure (un-polarized light) changes the (symmetric) residual stress of an optical fiber. This property can also be used in fine-tuning the splitting in the cladding mode so as to reduce the polarization dependence in the mode coupling between the core and the cladding modes.

[0093]   While certain exemplary embodiments have been described and shown in the accompanying drawings, it is to be understood that such embodiments are merely illustrative and not restrictive of the current invention, and that this invention is not restricted to the specific constructions and arrangements shown and described, since modifications may occur to those ordinarily skilled in the art.